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APPLICATION OF DUAL RESPONSE AND TOLERANCE ANALYSIS APPROACHES FOR ROBUST DESIGN OF SPOT WELDING PROCESS

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ABSTRACT

High quality products, processes and services are achieved at least cost through robust design. It is tried by many methods namely Dual Response approach, Tolerance analysis approach using response surfaces, Taguchi methods, Optimization Techniques etc. This paper aims at the robust design by Dual Response and Tolerance analysis approaches for the resistance spot welding characteristics of low carbon steel sheets.

Key word: Robust Design, Welding Process

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1. INTRODUCTION

Low carbon steel sheets are employed for deep drawing and other forming operations used in the manufacture of automobile parts and domestic appliances. These steels have good forming qualities as there is less carbon to interfere with the planes of slip; also the amount of carbon presents no particular difficulties in welding [1].

Resistance welding is based on the well-known principle that, as a metal impedes the flow of current, heat is generated. The amount of heat generated is a function of current, resistance between the sheets and the weld time of the process. Heat obtained also raises the temperature of electrodes and consequently the Heat Effected Zone is formed adjacent to the nugget of weld spot [2]. Hence the weld quality is governed by the proper selection of the process parameters [3].

High quality products and processes are achieved through robustness in the design aspects. Three different approaches to robust design are commonly used namely, inner-outer array approach advocated by Taguchi, Dual Response approach, and Tolerance Analysis approach by using Response surfaces [4].

Taguchi quality design technique was adopted for welding dissimilar materials of various thicknesses by varying the parameters like current and weld time to obtain the optimal values [5, 6].

Tensile strength increases rapidly with increasing current density. Excessive current density will cause molten metal expulsion, weld cracking and lower mechanical strength properties. Similarly during spot welding operation, some minimum time is required to reach melting temperature at suitable current density. Excessive long weld time will have the same effect as excessive amperage on base metal [7]. The optimal process parameter levels and the tensile shear strength of Joints have been evaluated for CRCA steel sheets by using Taguchi method [8].

The metallurgical characteristics, hardness, microstructure correlation, interfacial failure mode transition and mechanical performance of steel resistance spot welds under quasi-static, fatigue and impact loading conditions was studied in High strength steel employed in automotive industry [9].

Optimization techniques with the objectives of maximizing the strength, efficiency or minimizing the stress, weight under given constraints also can be used for quality augmentation [10].

2. EXPERIMENTAL WORK

2.1. Parent metal

Low carbon steel is extensively used in shallow and deep drawing operations employed in automobile applications. In the present work, C07 steel sheets of 2mm thickness are undertaken for the purpose of optimizing resistance spot welding parameters. The chemical composition and mechanical properties of the steel are given in Table 1.

2.2. Resistance Spot Welding

It is most widely used form of electrical resistance welding process. The sheet metals to be joined are held between two electrodes under pressure and high amperage is sent. The coalescence is produced in relatively small area by the heat obtained with the resistance between the faying surfaces. Welding process is carried out on resistance spot welding machine shown in Figure 1. The spot weld joints are made by

trial runs and parameters range is identified. Welding current and welding time are the two parameters taken for the purpose of making joints. These are presented in Table 2.

2.3. Mechanical Property Evaluation

Various loading conditions can be imposed on spot welds and are classified into two groups namely loading conditions which impose tensile stress at sheet-sheet interface; Cross tension, peel, CP and Chisel test are categorized into this group and the second group comprises of the loading conditions which impose shear stress at sheet-sheet interface; The Tensile shear test and torsion test are categorized into this group.

The specimens were prepared from the lap joined work pieces and the tensile shear test is conducted on Universal Tensile Testing Machine. A typical joint fabricated is shown in Figure 2. The total load applied for each of the joints is measured and compiled in Table 3 and Table 4 respectively.

2.4. Robust Design

In Robust Design the objective is to estimate the effect that the targets of the input variables have on the variation of the output and select the set of targets that minimize the variation while achieving the desired average.

Dual Response Approach involves running a response surface study where both the average and deviation of the output are analyzed. Here it is assumed that the objective is to minimize the variation.

In Tolerance Analysis approach the average of the study is taken with an objective to meet the target and attain the optimal values [11].

3. RESULTS AND DISCUSSION

The tensile strength of the joints has been measured under the chosen input parameters and is given in Table 3 and Table 4. They are used in computing the average and standard deviation. The estimates of the average and standard deviation for each target are depicted in Table 5. Quadratic polynomials are fit to these values using regression analysis. The equation is in the form of $b_0+b_1t_x+b_2t_x^2$and the coefficients are computed from the design matrix and the estimates of average and standard deviation. The design matrix (X) is in the form $\begin{bmatrix} 1 & t_{1x_i} & t_{1x_i}^2 \\ 1 & t_{2x_i} & t_{2x_i}^2 \\ 1 & t_{3x_i} & t_{3x_i}^2 \end{bmatrix}$ and the coefficients are computed [4, 11] by using the matrix algebra principles $(X^TX)^{-1}$ (X^TY). The resulting equations for the average and standard deviation of strength of joints are given in Table 6.

3.1. Dual Response Approach

In this approach a response surface is built for average and standard deviation of the output. The equation is used to minimize variation while achieving desired average. The equation for average is ignored and kept the objective to minimize the variation. An estimate of the target parameters for minimum variation is obtained by taking the derivative of standard deviation given in Table 6.

$\frac{d(\sigma_y)}{dt_{x_1}} = 0$ and $\frac{d(\sigma_y)}{dt_{x_2}} = 0$ then

$t_{x_1} = 10{,}200\ Amp$ and $t_{x_2} = 24.9\ cycles$

3.2. Tolerance Analysis Approach

This approach uses the equation for the average and the equation for standard deviation is ignored. Thus in this approach the response study of the output average (y) equation given in Table 6 is taken and tolerance analysis is conducted. A sample computation procedure for the input target weld time is given below:

$y = 8.8 - 0.015t_{x_2} + 0.001\ t_{x_2}^2$

Then

$$\sigma_y = (0.015\sigma_{x_2})^2 + (0.001)^2 + \left(4t_{x_2}^2\sigma_{x_2}^2 + 2\sigma_{x_2}^4\right) + 4\,(-0.015)(0.001)t_{x_2}\sigma_{x_2}^2$$

Plugging the input standard deviation in the above equation and later subjected to differentiation for optimality condition. The optimal value obtained for weld time is t_{x_2}= 25.3 cycles. Similarly optimal value for weld current is $t_{x_1} = 9{,}700$ Amp. These optimal values are compiled in Table 7.

4. CONCLUSION

The dual response approach identifies the variation of strength of joints made and there by the optimized values of target are identified. In this method it is found that weld current of 10,200 Amps and the weld time of 24.9 cycles are the optimal values.

While in Tolerance Analysis approach the variation of strength of joints is found by plugging in the variation of input and the covariance as per Variation Transmission Analysis [11]. In this method it is found that weld current of 9700 Amps and weld time of 253 cycles are the optimal values. The difference in the optimal values is due to the type of method adopted. However the variation transmission (Tolerance Analysis) approach is taken as the best value as it considers the minimization of variation and thereby sets the input parameter [4]. It is the least expensive approach and outperforms the other approaches in terms of accuracy and precision.

Table 1 Chemical composition (%) and mechanical properties.

Designation	C	Mn	Si	S	Tensile Strength (MPa)	Hardness (HB)
C07	0.12	0.5	0.18	0.01	410	70

Table 2 Parameters for Resistance Welding Process

S. No	Welding Current (Amp)	Welding Time (Hz)
1	8000	20
2	10000	25
3	12000	30

Table 3 Tensile Shear Load with Variation in Welding Current

Welding Current t_{x_1} (Target)	Tensile Shear Load (KN)
8000	9.0, 9.0, 7.4, 8.1, 8.5, 8.2
10000	9.7, 10.6, 8.5, 9.8, 10.2, 9.4
12000	10.2, 9.2, 8.9, 9.3, 9.5, 7.7

Table 4 Tensile Shear Load with Variation in Welding Time

Welding Time t_{x_2} (Target)	**Tensile Shear Load (KN)**
20	9.0, 10.6, 8.5, 8.1, 9.5, 7.7
25	9.7, 9.2, 8.9, 8.2, 8.5, 9.8
30	10.2, 9.0, 7.4, 9.3, 10.2, 9.4

Table 5 Estimate of Average and Standard Deviation of Tensile Shear Load

Estimate (y)	t_{x_1}			t_{x_2}		
	8000	**10000**	**12000**	**20**	**25**	**30**
Average	8.37	9.7	9.13	8.9	9.05	9.25
Standard Deviation	0.5735	0.658	0.7542	0.9579	0.6411	0.9410

Table 6 Regression equations for average and Standard Deviation Estimates

Parameter	**Average**	**Standard Deviation**
Weld Current	$y = -14.25 + 4.55t_{x_1} - 0.2162\, t_{x_1}^2$	$\sigma_y = 0.3525 - 0.0159\, t_{x_1} + 0.0078\, t_{x_1}^2$
Weld Time	$y = 8.8 - 0.015\, t_{x_2} + 0.001\, t_{x_2}^2$	$\sigma_y = 10.6289 - 0.8048\, t_{x_2} + 0.0161\, t_{x_2}^2$

Table 7 Optimal Values of Target

Approach	**Target (Input)**
Dual Response	$t_{x_1} = 10200\ A$ $t_{x_2} = 24.9\ cycles$
Tolerance Analysis	$t_{x_1} = 9700\ A$ $t_{x_2} = 25.3\ cycles$

Figure 1 Resistance Spot Welding Machine

Figure 2 A typical Spot Welded Joint

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